# FOREWORD

This COFORD report on carbon sequestration and storage in Irish forests is an important and timely publication. It clearly sets out the current and potential contribution of Irish forests to carbon storage. This information is vitally important because of commitments we have entered into, following the signing of the 1997 'Kyoto Protocol' to the UN Framework Convention on Climate Change. Under the protocol Ireland has agreed to reduce its $CO_2$ emissions to 13% above 1990 levels, by the period 2008-2012. This is against a background of the recent ESRI forecast that Irish greenhouse gas emissions will rise to 32% above 1990 levels by 2010.

Worldwide, forests are the largest landbased sinks of carbon. Their potential contribution to the lessening of global warming has been well established. In Ireland the national afforestation programme has the single largest potential to reduce net $CO_2$ emissions during the Kyoto timeframe. Critical to making this impact will be the attainment of the planting targets under the government's strategic plan for the forestry sector. These targets are important not only in the context of rural development and building the forest industry, but to offset the growth in fossil fuel consumption that is forecast over the next decade.

The estimates of carbon storage in forests have been arrived at using the best available information. There is still much work to be done in determining the contribution of forest soils to carbon storage. Other assumptions in the models will need further elaboration and research. However I am confident that this work is the most authoritative estimate of the current and potential carbon storage of our forests. In conclusion, I believe that the report will be useful not only to the forestry sector, but to policy makers and planners in many other spheres.

David Nevins
Chairman
COFORD
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# GLOSSARY OF TERMS

| | |
|---|---|
| Anthropogenic: | man made. |
| Biomass expansion factor (BEF): | is an estimate of the ratio of total above and below ground biomass to stem wood biomass. i.e. $\frac{\text{Above + Below Ground Biomass}}{\text{Stemwood Biomass}}$ |
| Carbon sequestration: | is the fixing of carbon in the organic compounds which make up the body of a tree. |
| Carboxylation: | is the fixing of carbon in plants through the process of photosynthesis. |
| Current annual increment (CAI): | is the annual volume increment of a forest crop at any point in time. |
| Mean annual increment (MAI): | is the average annual volume increment of a forest crop from planting to any point in time. |
| Oxidation: | organic matter decomposition and decay caused by living organisms. |
| Radiative forcing potential: | the ability of greenhouse gas emissions to warm the earth's atmosphere. |
| Yield Class (YC): | average annual volume of wood produced by a forest crop over the rotation ($m^3$/ha/an). |

# Executive Summary


Currently, there is increasing interest in carbon sequestration by forest crops as a means of mitigating greenhouse gas emissions. This review was compiled to establish the information available at present on carbon storage in forest plantations, with particular reference to the Irish situation.

With the available information, a preliminary estimate was made of the amount of carbon currently stored in Irish forests. An estimate was also made of the amount of carbon which could potentially be stored in forests established since 1990. Forests established since 1990 are eligible for inclusion in the calculation of carbon sequestration for the Kyoto period 2008-2012. The calculations indicate that:

- The average rate of carbon storage in Irish forest plantations is approximately 3.36 tonnes of carbon per hectare per year.
- By the year 2012, if planting targets are achieved, carbon sequestration by new (afforestation) forest plantations could offset 31% of the surplus $CO_2$ emissions in Ireland. If planting reaches 80% of the target, carbon sequestration by new forest plantations could offset 27% of the surplus $CO_2$ emissions. If planting reaches 60% of the target, carbon sequestration by new forest plantations could offset 23% of the surplus $CO_2$ emissions and if planting reaches 50% of the target, carbon sequestration by new forest plantations could offset 21% of the surplus $CO_2$ emissions.
- In the case of greenhouse gas ($CO_2 + CH_4 + N_2O$) emissions, by the year 2012, if planting targets are achieved, carbon sequestration by new (afforestation) forest plantations could offset 43% of the surplus Irish greenhouse gas emissions. If planting reaches 80% of the target, carbon sequestration by these forests could offset 38% of the surplus greenhouse gas emissions. If planting reaches 60% of the target, carbon sequestration could offset 33% of the surplus greenhouse gas emissions and if planting reaches 50% of the target, carbon sequestration could offset 30% of the surplus greenhouse gas emissions.
- If a model based on mean annual increment (MAI) is used to estimate carbon sequestration by forests during the Kyoto period (2008-2012) the estimates of carbon sequestered may be higher than those calculated using current annual increment (CAI) because CAI for new or young forests will be less than maximum mean annual increment (MMAI) during that period.

Other important points concerning carbon storage in forest plantations which arise from this review include the following:

- To increase the net amount of carbon stored in forest plantations, new land must be continually planted so that carbon fixation by forest growth will be greater than carbon released as a result of the utilization of wood products and soil organic matter decay.
- Irrespective of species, an increase in yield class increases carbon storage in all pools.
- The soil carbon pool accounts for the largest proportion of carbon storage (ca. 50%) in the tree-soil-product system.
- The effects of management practices on carbon storage in a forest plantation varies with the amount of disturbance caused to the site.

Although the model used in this review is the most suitable one currently available for the estimation of carbon storage in Irish forests, it requires adaptation to the Irish situation in order to provide more accurate estimates. The main factors which need to be addressed are:

- The suitability of the British Forestry Commission yield models in predicting the growth of Irish forest crops, particularly Sitka spruce crops.
- The accuracy of the biomass expansion factor (BEF) used in the model for Irish forest crops.
- The lack of information available on soil carbon dynamics in Irish forests.

The species profile of the Irish forest sector allows for carbon sequestration in both the long and short terms. If planting targets are achieved new Irish forests (post 1990) could sequester 6.34 MtC[1] during the period 2008-2012.


1 MtC = one million tonnes of carbon

# Introduction and Objectives

During the Kyoto conference in Japan, 1997 (UNFCCC, 1997), industrialised countries committed themselves to reduce their emissions of greenhouse gases (Schneider, 1998). Compliance with these commitments involves strategies which will reduce emissions from anthropogenic sources and also enhance the storage of greenhouse gases in natural ecosystems. This refers in particular to the storage of atmospheric carbon dioxide ($CO_2$) as organic carbon in soil. Ireland made a commitment under the Kyoto Protocol to reduce $CO_2$ emissions to 13% above 1990 levels by the period 2008-2012 (Clinch, 1999).

Carbon dioxide ($CO_2$), methane ($CH_4$) and nitrous oxide ($N_2O$) are the main greenhouse gases associated with climate change. Of these, $CO_2$ is responsible for 70% of the enhanced greenhouse effect, while $CH_4$ and $N_2O$ are responsible for 24% and 6% respectively (Houghton, 1997). $CH_4$ is produced largely by biological processes which occur in anaerobic environments. However, some reports (Bouwman, 1990; Crill, 1991) indicate that forest soils may, as a result of biological processes in oxidised layers, consume atmospheric $CH_4$. $N_2O$ is released from soils mainly as a result of microbial nitrification and denitrification. Forest ecosystems receiving high levels of nitrogen will produce large quantities of $N_2O$ (Ineson et al., 1998). As with all biological processes, the production or consumption of these gases is dependent on numerous soil and climatic factors. This report will deal primarily with $CO_2$, the principal greenhouse gas associated with forest ecosystems. $CH_4$ and $N_2O$ are responsible for a smaller proportion of the enhanced greenhouse effect and the contribution of these two greenhouse gases from forest ecosystems is small, even on a global scale.

In terrestrial ecosystems more carbon is stored in soils than in vegetation. However vegetation is the pathway through which soil carbon stores are changed. Trees have the highest carbon densities of all vegetation types, hence soils under forest vegetation often have a greater carbon store than soils under most other vegetation types (Birdsey, 1992 cited in Sampson, 1992; Cruickshank et al., 1998). Thus, forestry, through carbon sequestration and storage, has the potential to contribute to the mitigation of climate change.

Examination of the role of forests in global warming and carbon storage raises several issues which merit special consideration. These include:

- carbon storage in forest ecosystems and the effects of management and environmental factors on this storage,
- the role of forest ecosystems in mitigating anthropogenic carbon dioxide emissions,
- the effects of global warming on forest crops.

This report deals with the first two issues. Although global warming will affect the growth of all vegetation, including trees, it is beyond the scope of this report.

In this report, the current situation in Irish forests with regard to carbon sequestration is dealt with in two steps. First, the amount of carbon stored in forest crops is estimated using currently available data. Second, the areas which appear to be of prime importance in relation to the accurate estimation of carbon storage rates in Irish forests are highlighted. Using this approach, the paucity of appropriate data is revealed. This two step approach facilitates the identification of priority research areas and topics.

# 1. GLOBAL WARMING AND CLIMATE CHANGE

In recent years there has been growing concern about increasing levels of the radiatively active 'greenhouse' gases carbon dioxide ($CO_2$), methane ($CH_4$) and nitrous oxide ($N_2O$) in the earth's atmosphere. Increased concentrations of greenhouse gases in the atmosphere change the radiative energy balance of the earth by retarding energy transfer from earth to space (Savolainen and Sinisalo, 1994). This in turn may result in global warming. This change in energy flux from earth to space is called radiative forcing (Houghton et al., 1990). Greenhouse gases differ in their radiative forcing potential. According to Houghton et al. (1990), the global warming potential of various greenhouse gases for a period of 100 years (i.e. the warming effect of an emission of 1kg of each gas relative to that of $CO_2$) is: $CO_2$ = 1; $CH_4$ = 11; $N_2O$ = 270. Therefore radiative forcing can be used as a measure of the warming impact when greenhouse gas emission control strategies are evaluated.

Carbon dioxide is produced by a number of sources which include, the burning of fossil fuel and biomass, decomposition of organic matter and land-use change, primarily deforestation (Houghton, 1997). Deforestation refers mainly to tropical forest clearance. This usually involves the burning of unwanted (non-commercial) species and logging debris, leading to a release of $CO_2$ to the atmosphere (Detwelier and Hall, 1988). This type of clearance also exposes forest soils to higher temperatures and increased levels of soil moisture which make conditions more favourable for soil organic matter decomposition and $CO_2$ release. The amount of carbon released to the atmosphere as a result of deforestation, although significant, is far less than that released by burning fossil fuels (Detwelier and Hall, 1988; Vitousek, 1991; Sampson, 1992; Holdgate, 1995). Harrington (1987) reports that on a global scale, since 1958, land sources contributed only 4% of the increase in atmospheric $CO_2$ content, while fossil fuel burning contributed 96%. The primary source of atmospheric $CH_4$ is the microbial process of methanogenesis which occurs in oxygen depleted environments such as anaerobic soils, the digestive tracts of ruminants, and landfills. Other sources are combustion, biomass burning and coal mining. Atmospheric $N_2O$ is mainly produced by microbial nitrification and denitrification in soils. While scientific opinion differs about the likely impacts of rising levels of greenhouse gases on global climate, increases in air temperatures and a shift in weather patterns are widely predicted (Harrington, 1987; Houghton, 1997; Sweeney, 1997). These concerns about the threat of climate change have stimulated scientific interest in accounting for the sources and sinks of greenhouse gases and in exploring ways to slow their atmospheric accumulation by decreasing sources and increasing sinks.

Forests are of considerable interest in the attempts to increase carbon sinks since they sequester atmospheric $CO_2$ through photosynthesis during normal growth processes. Through photosynthesis the carbon in $CO_2$ is stored in the organic compounds which make up the body of the tree, mainly celluloses, hemicelluloses and lignins. Increasing forest production, so as to increase carbon sequestration, is now a well known technology in industrialised countries (Thompson and Matthews, 1989). Globally forests and forest soils represent large carbon reservoirs. Of the 550 GtC[1] in land biota about 350 GtC (64%) are sequestered in forests, and of the 1500 GtC in soil and detritus about 800 GtC (53%) are in forest soils (Cannell, 1996).

The concentration of $CO_2$ in the earth's atmosphere at present (ca. 360 ppmv) is approximately 30% higher than levels before the Industrial Revolution (Sampson, 1992; Houghton, 1997). On average, global levels are currently increasing annually by about 0.4%, adding 3.4 Gt of $CO_2$ to the atmospheric reservoir each year (Houghton, 1997). It has been estimated that approximately 7 Gt of $CO_2$ per year are being released to the atmosphere by fossil fuel combustion. Of this, 3.6 Gt are absorbed by oceans and terrestrial vegetation and 3.4 Gt are released annually to the atmosphere (Figure 1). Smaller amounts are released by deforestation in tropical areas.

Forests play an important role in the global carbon cycle and have the potential to significantly mitigate the effects of greenhouse gas emissions through the conservation and expansion of forest resources (Sedjo, 1989). The proposition of carrying out a large scale global afforestation programme in order to offset anthropogenic $CO_2$ emissions has received attention. Nilsson and Schopfhauser (1995) found that, over a 100 year period, a global afforestation programme of 345 million hectares could sequester approximately 30% of anthropogenic $CO_2$ emissions.

Ultimately the only way to prevent the increase in atmospheric $CO_2$ concentrations is to slow down or halt both the combustion of fossil fuels and the loss of carbon stored in soils and vegetation (Marland, 1988). While young fast-growing trees can take up relatively large quantities of $CO_2$, over a period of decades, as the

1 GtC = one giga tonne of carbon = one thousand million tonnes of carbon

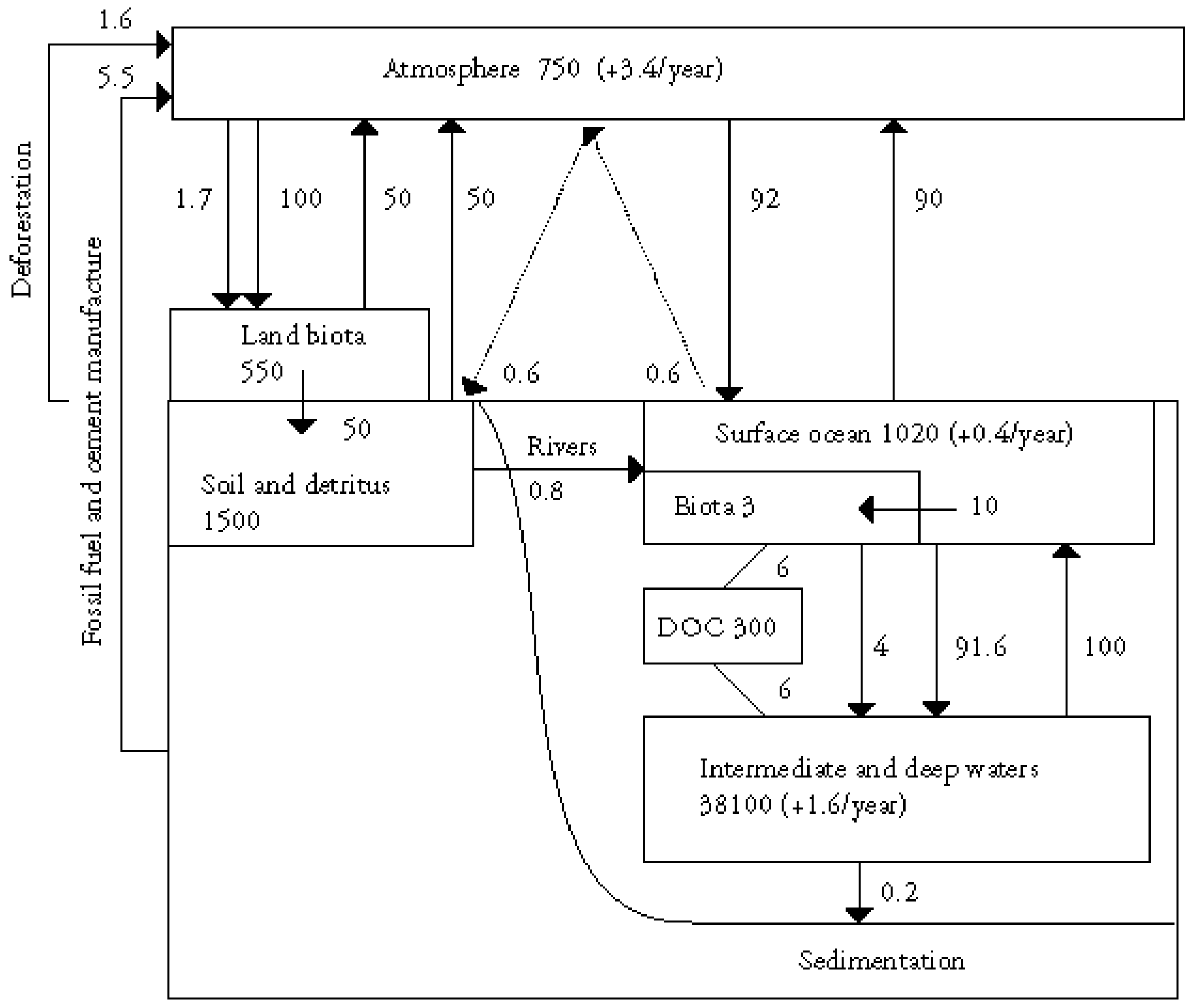


Figure 1. The global carbon cycle, pools and fluxes in Gt and Gt/year.
Source: Cannell (1995).

trees mature, their growth rate, and consequently their rate of $CO_2$ uptake, will decline. Forests therefore, offer no long term solution to the reduction of atmospheric $CO_2$ concentrations while humans continue to use fossil fuels. Forests can, however, contribute substantially to the stabilisation of atmospheric $CO_2$ levels until alternatives to existing energy sources are developed (Sedjo, 1989; Vitousek, 1991).

# 2. CARBON STORAGE IN FOREST ECOSYSTEMS

In forests, carbon is fixed in the trees by photosynthesis (carboxylation). It is eventually returned to the atmosphere by autotrophic respiration and processes of organic matter decomposition and decay involving other organisms (oxidation). There is a net gain of carbon in the system as long as the net inputs by carboxylation exceed the net outputs by oxidation. This will be reflected in a net increase in the size of the carbon pools. Although forests are continuously recycling carbon, the period of sequestration by net storage in vegetation and soil can range from years to centuries. The time scale depends on species, site conditions, disturbance and management practices (Cannell, 1995).

The three main carbon pools arising from forests are the biomass, soil and product pools. Each pool has an equilibrium value (maximum long term average) which in each case is much less than the maximum peak values. Peak values occur at the end of each rotation in the biomass pool and at the beginning of each rotation in the product and soil pools. This has been outlined by Cannell (1995) (Figure 2). Carbon stored in the biomass at the end of each rotation is transferred to either the product or soil pool. In the product pool there is a peak value at the start of each rotation, which occurs as a result of a transfer of wood from the previous rotation. As the various products decay, this peak value decreases over the length of the subsequent rotation. The soil carbon pool value also peaks at the same time as that of the product pool. This latter is due to increased inputs of litter and harvesting debris. These levels also decrease and level off over the following rotation as a result of organic matter decay. The equilibrium value of each pool is much less than the peak value. It is the maximum amount of carbon, averaged over time, that the system can store when it has reached equilibrium. The time taken for the forest-soil-product system to reach equilibrium is determined by the slowest process in the system. If, for example, products and litter decay rapidly (over a period of one rotation) then the equilibrium value will be reached at the end of the first rotation. If however, the average decay time is much longer than one rotation, several rotations may be required for the ecosystem to reach equilibrium.

The sum of the three carbon pools can be divided into two components; (a) the total equilibrium carbon storage, (b) the average rate of carbon storage over a standard period, usually the first forest rotation (Figure 2).

The total equilibrium carbon storage is greatest when equilibrium storage is greatest for each of the components i.e. biomass, soil and products. This occurs when (i) the living forests attain a large biomass rapidly and for a long period before they are

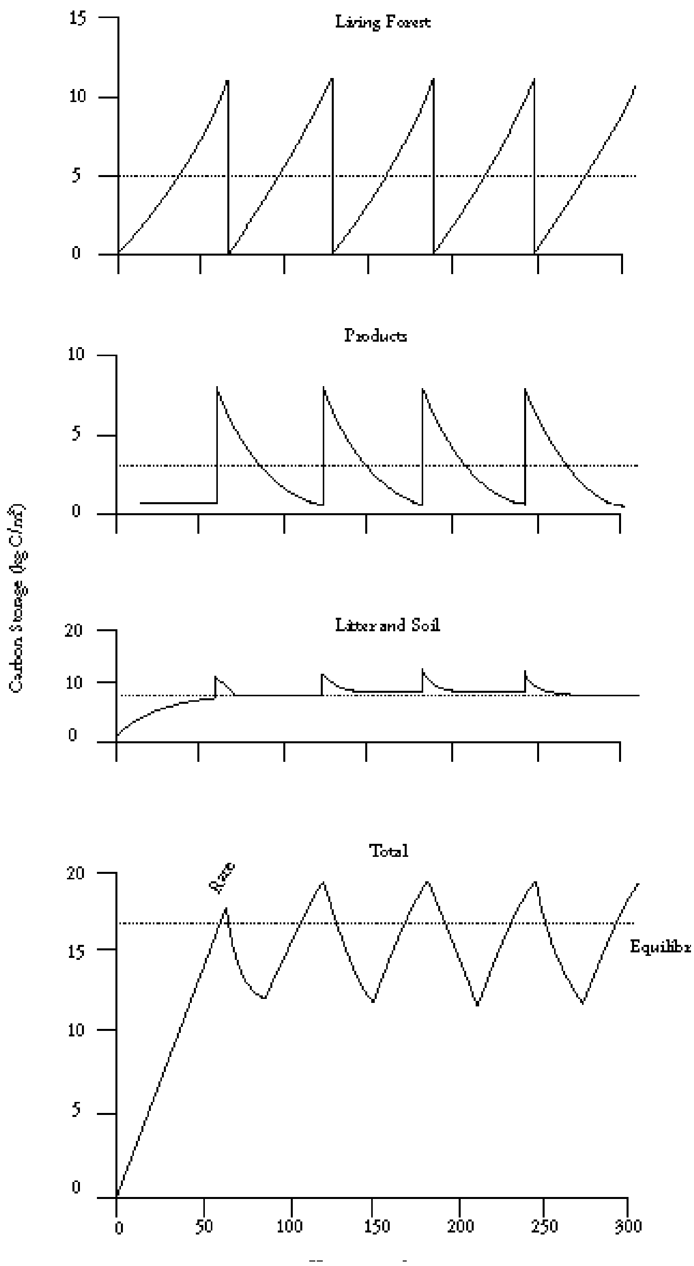


Figure 2. Simulated changes in the amount of carbon stored in living trees over five rotations. The horizontal broken lines mark the time-averaged equilibrium carbon storage values and the oblique broken line marks the mean rate of total carbon storage over the first rotation. Source: Cannell (1995).

harvested, so that the average amount of biomass on the site during a rotation period is large. This attribute depends primarily on species and site characteristics; (ii) when wood products have long lifetimes, so that the total store of undecayed products is large, and (iii) when litter decomposes slowly and a large fraction is transferred to recalcitrant soil organic matter pools. These latter two factors depend primarily on the species and climate.

The rate of carbon storage during a first rotation is primarily determined by the rate of growth of the forest. This depends upon the species, the site and management. Nabuurs and Mohren (1993), cited in Cannell and Milne (1995), used growth and yield tables along with published literature on the pools and fluxes of carbon in the forest-soil-products system to estimate both the rates of carbon storage and the equilibrium carbon storage in 16 global forest types. They showed that there is no relationship between long-term equilibrium carbon storage and the rate of storage over the first rotation. This is illustrated by the fact that in Britain, oak and beech plantations have much lower rates of carbon storage during the first rotation than conifer plantations such as Sitka spruce. However, these two forest types may have similar equilibrium carbon storage values (Table 1). This is mainly because oak and beech forests generally have larger biomass at the time of harvest and produce relatively longer-lived products than spruce forests. Although there is no relationship between equilibrium carbon storage and the rate of storage over the first rotation, the rate of storage has been found to be greatest in plantations with high yield classes. Clearly, if carbon storage is a management objective, consideration should be given to different forest types.

Table 1. Carbon storage characteristics of different forest types in Britain.
After: Cannell and Milne (1995).

| Species | Yield Class[1] $m^3$/ha/yr | Rotation[2] yr | Rate of C Storage tC/ha | Equilibrium C Storage tC/ha |
|---|---|---|---|---|
| Sitka spruce | 16 | 55 | 3.6 | 192 |
| Beech | 6 | 92 | 2.4 | 200 |
| Oak | 4 | 95 | 1.8 | 154 |
| Poplar | 12 | 26 | 7.3 | 212 |
| Lodgepole pine | 8 | 62 | 2.5 | 155 |

1 Yield class (YC) = Average annual volume of wood produced by a forest crop over the rotation

# 3. CARBON CYCLING IN FOREST PLANTATIONS

Forest management for optimum carbon sequestration requires an understanding of the major pools and fluxes of carbon in a forest and the changes over time in the sizes of these pools (Figure 3).

It is important when proposing increased carbon storage in forests to take into account the dynamics of natural and managed forests (Cooper, 1982). Biological storage of carbon on the suggested global scale (Nilsson and Schopfhauser, 1995) would involve setting aside large areas of land where trees would be allowed to grow to maximum biomass and thereafter remain in place. Cooper (1982) suggests that if a forest is managed for maximum sustained yield of wood or to maximise financial return, the forest ecosystem will rarely contain more than about one-third of the carbon that it could store if the crop was allowed to grow to maximum biomass. For forest crops to be effective in removing fossil fuel $CO_2$ from the atmosphere for periods longer than the period of near maximum growth rate, the harvested wood must be used to replace fossil fuels or utilised in such a way that it is prevented from being oxidised (decayed) and returned to the atmosphere as $CO_2$ (Marland, 1988).

The carbon balance between managed forests and the atmosphere depends critically on the frequency and intensity of harvesting, as well as on the lifetime of the harvested products. If forests are planted and harvested periodically, carbon is fixed in living trees during regrowth and put into storage in various wood products

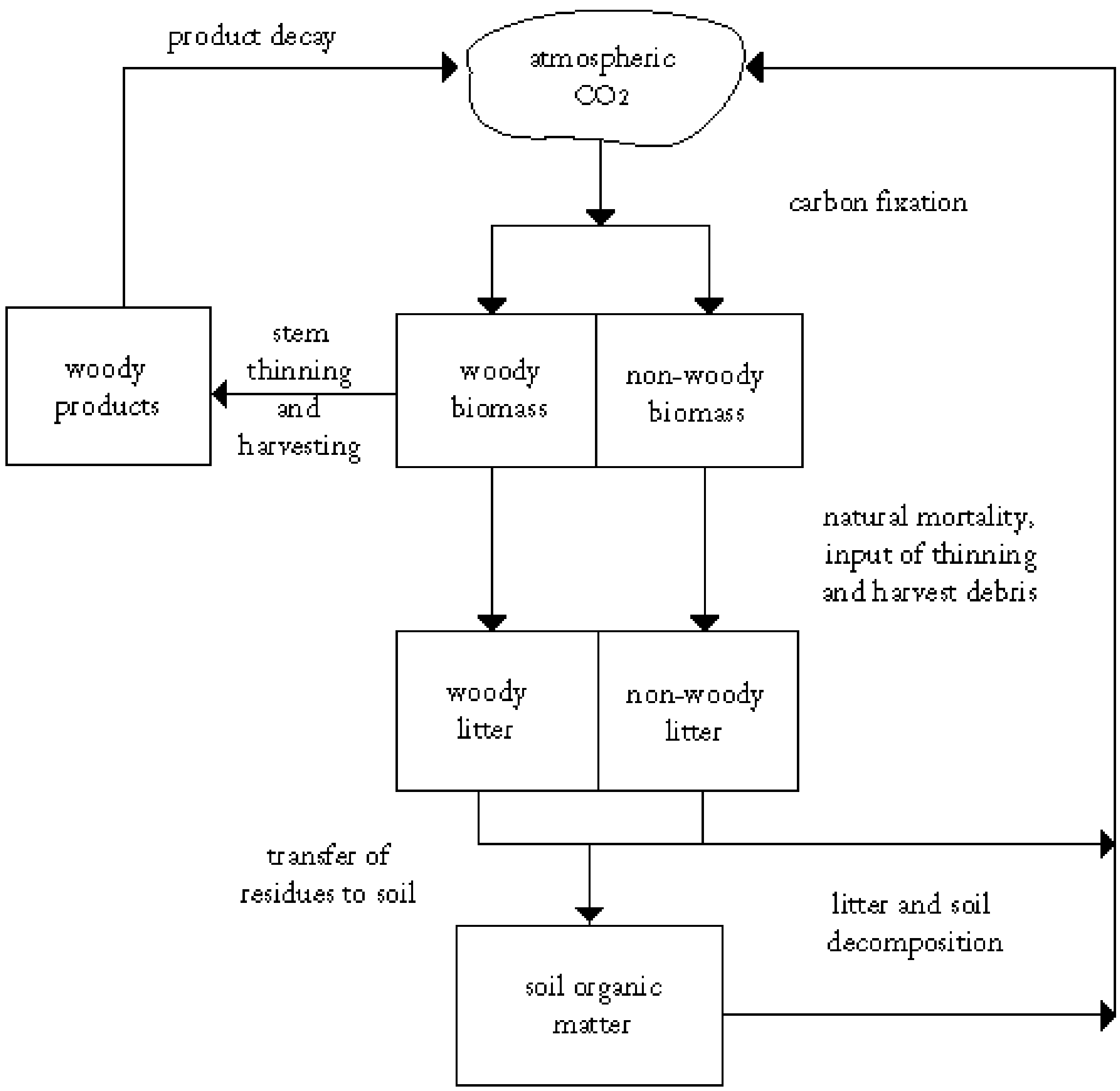


Figure 3. Carbon pools and carbon fluxes in a plantation forest ecosystem. Source: Cannell (1995)

and in various detrital and soil carbon pools. All of these subsequently decay on a variety of time scales. Repeated harvesting thus accumulates a stock of carbon only over a finite period, after which an equilibrium is reached and further carbon fixation by forest regrowth is balanced by the decay of wood products and soil organic matter with the release of $CO_2$. If new land is not continually being planted, eventually total forest biomass will no longer increase from one year to the next and the volume of wood harvested will equal the volume grown by the forest (Hollinger et al., 1993).

The amount of carbon sequestered in each of the pools at any one time varies over the length of any crop rotation. This applies to all species irrespective of yield class and can be clearly seen in Figure 2. However, it is also widely recognised (Dewar and Cannell, 1992; Dixon et al., 1994; Karjalainen et al., 1994) that, although the amount of carbon in each pool varies over time, the most important carbon store in the system is the soil pool which accounts for the largest proportion of carbon storage in the system (Figure 4).

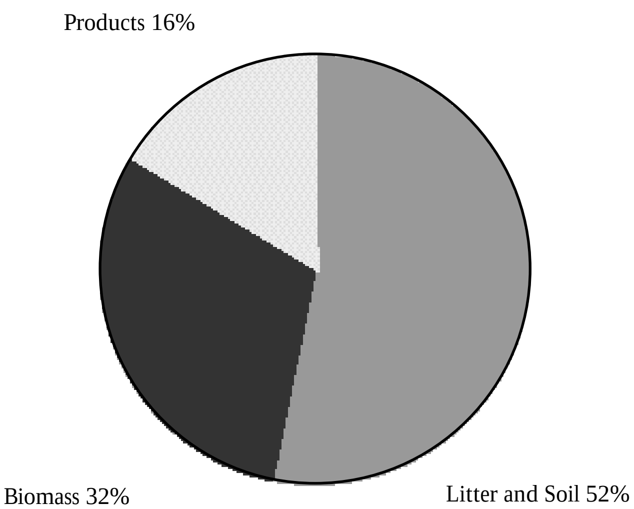


Figure 4. Carbon storage in forest ecosystem pools.
After: Dewar and Cannell (1992)

## 3.1 Biomass pool

The living forest is itself a carbon pool and will be a sink as long as the trees are growing. In Figure 3 woody and non-woody biomass are separated because of their different growth dynamics. Woody biomass increases in a sigmoidal fashion as the forest grows and is passed either to the forest floor as woody litter or is harvested. Non-woody biomass reaches maximum levels early in the rotation and usually all of it passes to the forest floor.

The rate of carbon sequestration varies with tree species. Dewar and Cannell (1992) compared eight contrasting types of forest and woodland plantations with growth rates and other characteristics typical of UK conditions (Table 2). Species that have the fastest growth, i.e. are assigned the largest yield classes, generally have the fastest initial rate of carbon storage. However, they do not necessarily have the greatest total storage at equilibrium. For example, the time-averaged carbon storage in trees in thinned beech (*F. sylvatica* L.) plantations of yield class 6 was greater than that in thinned spruce (*P. sitchensis* (Bong.) Carr.) plantations of yield class 12, because beech plantations exist for long periods with a large biomass. Species differences in rotation lengths, litter inputs and decomposition rates can also counteract the expected effects of differences in yield class on total carbon storage.

Dewar and Cannell (1992) conclude that in the UK, if the objective is to store carbon rapidly in the short term (20-30 years) and achieve high carbon storage in the long term (at equilibrium), the best option would appear to be poplar (*Populus* spp.) plantations growing on fertile land. Poplars have rapid juvenile growth giving high estimated carbon storage rates (7.3 tC/ha/an) over the first rotation and a large time-averaged carbon storage value in the tree-soil-product system (212 tC/ha). If the objective is to achieve high carbon storage in the medium term (50 years) without regard to the initial rate of storage, then plantations of any species of conifer with above average growth rates would suffice. In the long term (100 years), broadleaved plantations of oak and beech store as much carbon as coniferous plantations. Mini-rotations (8 years) of species such as willow (*Salix* spp.), store carbon rapidly over the first rotation but do not achieve high carbon storage at equilibrium because, on average, there is little carbon in tree biomass and little litter input.

An increase in yield class means an increase in the rate of carbon accumulation in the trees, a shorter rotation, and larger and more frequent transfers of carbon to the product and litter pools. Consequently, whatever the species, an increase in yield class increases the carbon storage in all carbon pools. This is demonstrated for Sitka spruce in Table 3. It has been estimated that

Table 2. Carbon sequestration in eight contrasting types of forests/woodland plantations typical of the UK. After: Dewar & Cannell (1992).

| Species | Yield Class $m^3$/ha/yr | Planting Espacement m | Rotation yr | Rate of C storage tC/ha/yr | Equilibrium C storage tC/ha |
|---|---|---|---|---|---|
| Willow, short rotation coppice | - | 0.3 | 8 | 5.9 | 93 |
| Poplar, unthinned | 12 | 2.7 | 26 | 7.3 | 212 |
| Southern beech, thinned | 16 | 1.7 | 28 | 4.6 | 179 |
| Sitka spruce, intermediate thinning | 12 | 1.8 | 59 | 3.0 | 167 |
| Scots pine, intermediate thinning | 10 | 1.8 | 71 | 2.7 | 178 |
| Lodgepole pine, intermediate thinning | 8 | 1.8 | 62 | 2.5 | 155 |
| Beech | 6 | 1.2 | 92 | 2.4 | 200 |
| Oak | 4 | 1.2 | 95 | 1.8 | 154 |

Table 3. The impact of increasing yield class on carbon storage after one rotation and at equilibrium. After: Dewar and Cannell (1992).

| Sitka spruce | YC6 | YC12 | YC16 | YC20 | YC24 |
|---|---|---|---|---|---|
| Rotation (yr) | 68 | 59 | 55 | 51 | 47 |
| Rate of C Storage (tC/ha/yr) | 2.5 | 3.0 | 3.6 | 4.1 | 4.4 |
| Carbon Storage after one rotation (tC/ha) | 170 | 177 | 198 | 209 | 207 |
| Carbon Storage at Equilibrium (tC/ha) | 134 | 167 | 192 | 208 | 211 |

an increase in yield class from 6 to 24 $m^3$/ha/yr, for Sitka spruce, can lead to an increase in total carbon storage (Figure 2) in the tree-soil-product system of about 60% (Dewar and Cannell, 1992).

## 3.2 Litter and soil pool

During the life of the forest, the litter pool continuously receives carbon from the forest in the form of dead foliage, roots, branches and whole trees, which then decompose. This decomposition returns some carbon to the atmosphere as a result of microbial respiration, and transforms a residual to a pool of soil organic matter.

In Northern Ireland the total amount of stored carbon in all vegetation is estimated to be 4.4 Mt. The corresponding figure for soil is 386 Mt (Cruickshank et al., 1998). Of the 4.4 Mt of carbon stored in vegetation, 2.4 Mt are found in forest crops and 63% of these forests are established on peat or peaty soils. Of the 386 Mt of carbon stored in soil, peat and peaty soils contain 162 Mt. It is clear from this and other sources (Ford-Robertson, 1997) that the soil is a vastly important carbon reservoir which accounts for a very large proportion of sequestered carbon. While the total amount of carbon stored in the soil is important, it is ultimately the change in soil carbon content over time that is of greatest importance in relation to atmospheric carbon concentrations. Harrison et al. (1995) estimate that a 1% loss in the total carbon stored in British soils due to global warming would amount to the equivalent of 1.4 times the total fossil fuel consumption at 1988 levels. Soil carbon fluxes are dependent on, among other things, the nature of the decaying material and the physical soil environment. Bouwman (1990) has reported that almost 50% of the carbon in a typical soil profile is found above a depth of 50cm and is relatively unstable. The remainder, found in the lower soil horizons, is more stable. The stability of soil organic matter, and hence soil carbon, is affected by numerous soil characteristics, which include, texture, structure and fertility as well as vegetation-soil effects. Modern practices such as fertilizer application, drainage and cultivation may cause a decline in soil carbon content, primarily by enhancing conditions for organic matter decomposition. Climate also affects the amount of carbon stored in soil (Cooper, 1982; Post et al., 1982; Harrison et al., 1995). In general, more carbon is stored with increasing precipitation and decreasing temperature. As the potential for forest biomass to sequester carbon is small in relation to annual fossil fuel emissions, it is ultimately the impact of forestry on the soil carbon balance which is of prime importance in carbon cycling.

### 3.2.1 Organic soils

Peatland forests account for a large proportion of the forest estate in Ireland. While no accurate figures are available, Farrell and Boyle (1990) estimated, that there were some 200,000 hectares of peatland forestry. Given the expansion of the forest estate throughout the 1990's this figure can be expected to have increased.

Virgin peatlands are carbon sequestering ecosystems. Peat formation continues so long as the net primary productivity exceeds the rate of decay. Within a peat-forming system there are two layers: (i) an aerobic zone above the water table, which is very shallow since the water table is usually close to the peat surface, and (ii) an anaerobic zone beneath the water table. Aerobic decay above the water table produces $CO_2$. The magnitude of these emissions is normally quite small due to the shallowness of the aerobic zone. Anaerobic decay beneath the water table produces $CH_4$. Although some of this $CH_4$ may be oxidised to $CO_2$ as it passes through the aerobic layer, most of it is emitted to the atmosphere. Thus, $CH_4$ emissions are generally much higher than $CO_2$ emissions in peatland ecosystems.

Forestry development precipitates a dramatic change in the carbon balance of virgin peatlands. Drainage lowers the water table which allows aeration of the surface peat and increases the depth of the aerobic layer. As a result aerobic decomposition, and therefore $CO_2$ emissions, are greatly increased. The magnitude of this increase depends on the efficiency of drainage and can vary from a doubling of $CO_2$ emissions (Silvola et al., 1996a) to a ten-fold increase (Silvola, 1986). Root respiration from the growing forest crop can account for 35-45% of $CO_2$ emissions (Silvola et al., 1996b). At the same time $CH_4$ emissions may be greatly reduced or cease (e.g. Moore and Roulet, 1993; Roulet et al., 1993; Fowler et al., 1995; Martikainen et al., 1995; Roulet and Moore, 1995). This is mainly due to the increased depth of aerobic peat which increases the potential for any $CH_4$ produced beneath the water table to be oxidised before reaching the atmosphere. There may even be a net uptake of atmospheric $CH_4$ (Glenn et al., 1993; Roulet et al., 1993; Roulet and Moore, 1995).

Whether the system remains a carbon sink or becomes a carbon source will depend on whether carbon sequestration by the forest crop can compensate for the increased carbon losses due to peat oxidation. A number of studies, the majority in Finland, have attempted to quantify the change in the peat carbon store following drainage for forestry. Laine and Minkkinen (1996) found that the net change in the original carbon store over 30 years following drainage was -0.14 tC/ha/an. However, an increase in the carbon store has also been found and this has been associated with more nutrient-poor sites types in the south of Finland (Minkkinen and Laine, 1998a). One possible reason for this, is higher post-drainage fine root biomass production, with carbon deposition near anaerobic layers (Finér and Laine, 1994), and a small post-drainage increase in $CO_2$ emissions from organic matter decay in these sites (Silvola et al., 1992). Following an extensive study of undrained and drained (ca. 60 years) sites in Finland, Minkkinen and Laine (1998b) concluded that carbon storage in peat in Finland is likely to have increased following drainage.

Studies in the former Soviet Union have found similar changes in the carbon store of peatlands drained for forestry (Vompersky and Smagina, 1984; Sakovets and Germanova, 1992; Vompersky et al., 1992). Studies from Norway (Braekke, 1987) and Scotland (Anderson et al., 1994) report much higher losses. These losses may be attributed to thermoclimatic differences (Meentmeyer, 1978) since microbial activity has been shown to increase with increasing temperature. The ambiguous nature of the results may also be due to the difficulty in measuring the changes in the carbon store, which are very small with respect to the total store, or the lack of a universal method for measuring them (Laine et al., 1992).

Forest management practices can have a major impact on the carbon balance. For instance, Laine and Minkkinen (1996) found that if no harvesting operations were carried out during the first 300 years following drainage, the tree stand would produce a carbon store of approximately 110 tC/ha. A standard thinning regime would reduce this carbon store by ca. 50%. Expressed as an average over the 300 years, drainage would increase the carbon store if there was no harvesting. If on the other hand harvesting was carried out the store would remain unchanged. Cannell et al. (1993) carried out a similar study of peatland forests in the United Kingdom. They found that at $CO_2$ emission rates of 0.5-1.0 tC/ha/an there is likely to be increased carbon storage in the whole system (i.e. peat, litter, biomass and products) for at least three rotations. However at soil $CO_2$ emission rates of 2-3 tC/ha/an, increased carbon storage might only occur in the first rotation, after which there would be a net loss.

Studies which examine the effect of forestry on the carbon balance in peatlands should also consider the change in radiative forcing potential following forestry development. This is because $CH_4$, the dominant greenhouse gas in virgin peatlands, has a much higher radiative forcing potential than $CO_2$, the dominant greenhouse gas in forested peatlands. Studies relating to this are limited. One such study by Laine et el. (1997) suggests that the greenhouse impact of peatland is decreased after drainage and will remain lower for a few hundred years. Although forestry development may convert a peatland from a $CH_4$ source to a $CH_4$ sink, the strength of this sink may be reduced by $CH_4$ emissions from drainage ditches. Both Roulet and Moore (1995) and Minkkinen et al. (1996) have observed $CH_4$ emissions from drainage ditches in the range <5 to >400 $mgCH_4/m^3/day$.

While most of the peatland forestry in Ireland is on blanket peatland, raised bogs, fens and industrial cutaway bogs have also been afforested. In a recent study, Byrne et al. (1999) found that forestry development transformed a blanket peatland from a net source of $CH_4$ to a weak sink and that $CO_2$ emissions were greatly increased. While none of the other site types mentioned here have been studied, forestry development can be expected to exert a considerable influence on the carbon balance. Drainage of intact raised bogs and fens will reduce $CH_4$ emissions and increase $CO_2$ emissions. Drainage of fens may also stimulate $N_2O$ emissions (Martikainen et al., 1993; Regina et al., 1996, 1998). Industrial cutaway peatlands present a different situation. The bare peat surface may act as a weak sink for $CH_4$ and there may be $CH_4$ emissions from flooded areas and drains. The rate of $CO_2$ emissions will depend on environmental conditions as well as on the degree of humification and nutrient status of the peat. Ground cultivation, such as the mixing of peat with the sub-peat soil, may stimulate oxidation and lead to an increase in $CO_2$ emissions. The time taken for these sites to become carbon sinks will depend on the productivity of the forest crop. The development of ground vegetation may play an important role in the carbon balance during the early stages of forest growth.

### 3.2.2 Wet mineral soils

Whether or not forestry development results in a change in the carbon content of mineral soils primarily depends on the soil carbon content prior to planting. When forests are planted on former forest land or organic soils, the net change in soil organic matter at the start and end of the rotation may be zero. However, when trees are planted on former agricultural land there is often a substantial build-up in soil organic matter (Dewar and Cannell, 1992). It is important to distinguish between agricultural land which has been formerly cultivated and used for tillage crops and that which has been used as pasture. Agricultural soils which have been continuously cultivated lose large amounts of organic carbon because cultivation accelerates the decomposition of soil organic matter (Mann, 1986). Crop residues also decompose relatively rapidly and crops leave less residue in the soil than trees (Vitousek, 1991). Soils which are under permanent pasture receive less disturbance and there is a greater return of litter to the soil than with tillage crops. It is generally agreed (Cannell and Dewar, 1995; Harrison et al., 1995) that afforestation on soils with depleted carbon content as a result of cultivation for agricultural purposes, may result in accumulation of carbon in both the mineral soil layers and as undecomposed litter. Afforestation of pasture land with species which accumulate large amounts of litter can result in the sequestration of considerable amounts of carbon. However on these sites, where the soil already contains substantial amounts of organic matter, additional carbon accumulation is usually restricted to the litter and surface soil layers.

Johnson (1992) presents a detailed review of the effects of various forest management practices on soil carbon storage. Although the studies reviewed show variable results, most show no significant change in soil carbon content due to harvesting unless it is followed by intense burning or cultivation. Cooper (1982) reports that harvesting stimulates decomposition of detritus as a result of higher soil temperature and moisture, as well as increased availability of the inorganic nutrients needed by decomposers. If, however, forest vegetation is re-established soon after harvesting, loss of soil organic carbon is relatively slight.

Cultivation prior to planting can result in large losses of soil carbon (Johnson, 1992). When discussing the changes in soil carbon due to disturbance it is important to be aware of both the initial soil carbon content and how sensitive this carbon is to disturbance. In general, there is a net loss of soil carbon with site preparation, the magnitude of which is dependent upon the severity of the disturbance. However, it is often not possible to separate soil carbon lost by displacement (i.e. not necessarily lost to the atmosphere as $CO_2$) from that which is lost due to decomposition.

As already mentioned, carbon storage in soils often increases with increasing precipitation. This is due to increased anaerobic conditions and hence decreased levels of soil organic matter decay. Drainage of wet mineral soils is therefore likely to reduce the store of soil carbon by increasing aerobic decomposition. Little documented evidence exists to support this, particularly when drainage is followed by establishment of a forest crop. Armentano (1980) cited in Bouwman (1990) agrees that drainage of wet mineral soils may lead to carbon release as a result of organic matter oxidation.

Cooper (1982) suggests that the reduction in carbon storage due to thinning is not large. Thinnings are intended, in part, to anticipate natural mortality and therefore mortality of individual trees should be minimal in intensively managed stands. Hence, thinning has little impact on carbon storage. However, Dewar and Cannell (1992) estimate that thinned plantations of YC 14 Sitka spruce stored about 15% less carbon than unthinned plantations. Thinning decreased the average amounts of carbon in all pools. The reduction of carbon storage was mainly due to decreased input of carbon to the litter pool both during the rotation and at harvest.

### 3.3 Products pool

The wood products pool contains the carbon in wood that is taken from the site in thinnings and at harvest. This carbon eventually decays to release $CO_2$ as a result of microbial respiration or burning. The net total carbon retained in wood (living trees plus products) depends greatly on the rates of growth of the trees as well as the end uses of the wood. The rapid carbon accumulation rates of many forests can not be sustained over the entire rotation. Although net primary productivity of forest plantations can remain high, respiration of accumulated biomass causes net storage of carbon to decrease rapidly. Maintenance of a strong sink for atmospheric carbon within forests therefore requires harvest. The fate of the harvested material determines whether tree plantations can represent a long-term sink for carbon. The quantity of carbon stored in wood products depends on the lifetime of the product and these lifetimes are poorly known. Dewar and Cannell (1992), using an exponential model, assumed that 95% of wood product carbon from one rotation was lost over the next rotation. At an equilibrium over many rotations they found that only 16% of total carbon storage was in wood products. Over a similar time span, with forest plantations which produce largely short-lived products such as pulp, total carbon storage in wood products might be substantially less.

# 4. THE POTENTIAL OF EXISTING FOREST ESTATE FOR CARBON STORAGE

Marland and Marland (1992) suggest that the most effective strategy for using forest land to minimise increases in atmospheric $CO_2$ will depend on the current status of the land, the productivity that can be expected, the efficiency with which the harvested logs are used and the time perspective of the analysis. For forests with large standing biomass and low productivity the most effective strategy is to protect the existing forest. For land with little standing biomass and low productivity, the most effective strategy may be to reforest or otherwise manage the land for forest growth and carbon storage. Where high productivity can be expected, the most effective strategy is to manage the forest for a harvestable crop and to use the harvest with maximum efficiency either for long-lived products or to substitute for fossil fuels. The longer the time perspective, the more likely that harvesting and replanting will result in net carbon benefits. Growth rates in managed forest plantations can be optimised by planting fast growing species on optimum sites and employing advanced silvicultural techniques.

The idea of converting old-growth forests to faster growing young plantations in an attempt to increase carbon storage rates may seem reasonable at first glance. However, this suggestion disregards the critical factor, that it is the total amount of carbon stored within a forest ecosystem rather than the annual rate of uptake which is important. As already indicated (Sections 2 and 3.1) species with fast initial rates of carbon storage do not necessarily have the greatest carbon storage at equilibrium. Therefore although old-growth forests may make no net contribution to $CO_2$ storage, as their large uptake in photosynthesis is balanced by an equally large release in autotrophic respiration, replacing them with young crops will not necessarily increase carbon storage rates in the long term. Dewar (1991) reports that studies have shown that the average stock of carbon in living trees and soils of managed forests can be as little as 30% and 70%, respectively, of the carbon stock in old-growth forest. Harmon et al. (1991) report that conversion of old-growth forests to younger forests under current harvesting and use conditions has added and will continue to add carbon to the atmosphere. The amount of carbon added by conversion may vary among forests, depending on their equilibrium storage capacity and the difference between the timber rotation age of the proposed replacement crop and the age of the old-growth forest within the ecosystem. The same authors suggest that a 450 year old natural Douglas fir-hemlock (*Pseudotsuga-Tsuga*) stand can store 2.3 times more carbon than a 60 year old plantation of Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco). Vitousek (1991) also claims that there is twice as much carbon stored in an area of old-growth forest than there is in a similar area converted to young plantation. It appears, therefore, that the conversion of old-growth forests to fast growing plantations may be counterproductive in terms of carbon sequestration.

# 5. Models for the evaluation of carbon sequestration in forest plantations

While many models have been developed to evaluate carbon sequestration in various ecosystems, one of the few which encompasses the entire tree-soil-product system and tracks the flow of carbon from the trees to soils and products in a dynamic fashion is that proposed by Dewar and Cannell (1992). This model has been used to explore the options for storing carbon in plantations with different growth rates and of different species. A detailed description of the model is given in Dewar (1991). It is based on the British Forestry Commission yield models for forestry management (Edwards and Christie, 1981) and a rotation length corresponding to the age of maximum mean annual increment (MMAI). It takes account of the carbon cycle throughout a forest rotation by including aspects such as the transfer of material between pools, rates of biomass and soil organic matter decomposition and the product lifetime of the harvested material.

Gallagher (1998) used a simpler model to estimate annual carbon sequestration rates in Irish forests. However, this model did not take into consideration the carbon sequestered in either the soil or product pool. It estimated the carbon stored in the total standing biomass of a forest plantation at a particular moment in time. This estimate was obtained from a calculation based on yield class, stemwood basic density, wood carbon content and a biomass expansion factor (BEF) of 1.3. This latter is an estimate of the ratio of total above and below ground biomass to stemwood biomass.

While the contribution to carbon storage of the product pool is generally agreed to be quite small (ca. 16%) relative to the whole tree-soil-product system, the contribution to carbon storage by the soil pool is the most important in the system (ca. 52%) and should not be overlooked. Therefore, as the Dewar and Cannell (1992) model is the more comprehensive and widely documented of the two, it will be used, as far as possible, to estimate the carbon storage in Irish forests. Attempting to calculate the carbon storage in Irish forest plantations using this model serves two main purposes. Firstly, it gives an estimate of the carbon storage potential of these plantations. Secondly and perhaps more importantly, it highlights the areas where research information is lacking from an Irish perspective and in particular the fact that there is little information available on the carbon content of, and carbon accumulation in, forest soils.

It is worthy of note that small changes in any of the model components could lead to considerable differences in the carbon sequestration estimate obtained. Dewar and Cannell (1992) carried out a sensitivity analysis on the major assumptions and parameter values in their model. They concluded that the parameters of greatest uncertainty or those which had a major impact on carbon storage were the fractions of total woody biomass that occur in branches and woody roots. This relates to the problem of estimating the ratio of total to merchantable biomass. Litter and soil organic matter decomposition rates were also found to have an impact on carbon storage, in particular the rate of fine root turnover. This turnover has long been recognised as an important but poorly understood process which could potentially transfer a relatively large proportion of carbon to the soil pool. Parameters which Dewar and Cannell (1992) found to have little impact on carbon storage include stemwood basic density and the fraction of carbon in biomass.

Both carbon content and wood basic density are reported to vary with species. Most of this variation, however, is covered in the sensitivity analysis of Dewar and Cannell (1992). Their model uses standard values of 50% for the carbon content of wood (0.5) and 0.35 kg/m$^3$ for wood basic density. From the available data for wood basic density (Ward, 1975; Dewar and Cannell, 1992; Karjalainen et al., 1994; Milne et al., 1998) it appears that a value of 0.35 kg/m$^3$ (±0.05) is quite accurate for conifers. However values for broadleaves such as oak and beech may be slightly higher at perhaps 0.55 kg/m$^3$. Although data on wood carbon content for various species is sparse, a value of approximately 0.5 is widely accepted to be the mean fraction of carbon in dry wood. Matthews (1993) describes the main methods of assessment of the carbon content of wood and concludes that, although there is some variation in the carbon content of different species, a value of 0.5 is a reasonable estimate. Thompson and Matthews (1989) give slightly lower estimates of 0.42 for conifers and 0.45 for broadleaves. In Dewar and Cannell's model changing these values for basic density and carbon content by ±0.05 had an insignificant impact on the predicted total carbon storage in forest ecosystems.

Table 4. Biomass distribution for a Sitka spruce plantation. After: Carey and O'Brien (1979).

| | Dry Weight kg/ha | | | | |
|---|---|---|---|---|---|
| | Stem | Crown | Roots | Total | BEF |
| 33 yr old crop | 201,676.3 | 102,730.7 | 56,809.9 | 361,216.9 | 1.8 |

Although no such sensitivity analysis has been carried out using Gallagher's model, it appears that using a BEF of 1.3 to obtain an estimate of below ground biomass, total stemwood and branches may introduce a significant underestimate. Winjum (1998) reported a BEF of 1.3 as the proportion of total aboveground biomass to commercial biomass, but this took no account of woody roots. Although the two models discussed above differ in their method of estimating carbon sequestration it appears that similar parameters in both models are responsible for the largest areas of uncertainty.

The BEF for any forest crop will vary with crop density and age. Nevertheless, it is important that this factor is measured accurately. Dewar and Cannell's sensitivity analysis showed that doubling the standard BEF value resulted in a 73% change in the estimated total carbon storage using their model. Despite this, reported estimates of BEFs for forest crops differ. Dewar and Cannell (1992) give an estimate of 1.4 using their standard values while Gallagher (1998) used a value of 1.3 in his calculations and, as previously mentioned, Winjum (1998) gives a BEF value of 1.3 which excludes below ground biomass. There is much uncertainty over the appropriate BEF for different forest crops. Hence, there is a need for considerable research in relation to the appropriate BEF for Irish forest crops.

The only published data available for biomass distribution in Irish forest crops are those produced by Carey and O'Brien (1979) for a 33 year old, yield class 14, Sitka spruce crop (Table 4). From these figures a BEF of 1.8 can be calculated. This is higher than the estimates used by both Dewar and Cannell (1992) and Gallagher (1998). However, it should be noted that this crop was planted at a high density (3,760 stems/ha) and received no thinning. As a result it may not be considered to be representative of current silvicultural practice.

Wills (1999) presents biomass data for a number of Sitka spruce crops in Ireland ranging in age from 4 to 29 years. Using this biomass information (Table 5) BEF's ranging from 1.7 to 2.8 were calculated. These figures indicate that the BEF figure (1.4) used by Dewar and Cannell (1992) may represent a significant underestimate for Irish Sitka spruce crops, especially as the method used by Wills to estimate biomass distribution took no account of fine roots. The root systems examined were cut off and excavated at a radius of 1m from the main stem.

Data from these Irish Sitka spruce crops are insufficient to derive a BEF for the country as a whole. The different values obtained highlight the variation of this factor and the need for more data. The variation shown in these estimates highlights the fact that the BEF used to convert merchantable biomass (as obtained from yield models) to total biomass is uncertain. The situation is similar for broadleaf crops, with no published data available for biomass distribution, particularly in semi-mature and mature crops.

Table 5. Biomass distribution for Sitka spruce plantations. After: Wills (1999).

| | Dry Weight kg/tree | | | | |
|---|---|---|---|---|---|
| | Stem | Crown | Roots | Total | BEF |
| $4\frac{1}{2}$ yr old crop | 2.43 | 2.74 | 1.75 | 6.92 | 2.8 |
| 6 yr old crop | 5.99 | 7.57 | 3.29 | 16.85 | 2.8 |
| 19 yr old crop | 73.05 | 29.29 | 18.67 | 121.63 | 1.7 |
| 29 yr old crop | 104.79 | 57.42 | 45.72 | 207.93 | 1.9 |

# 6. CARBON SEQUESTRATION IN IRISH FORESTS

During the course of this study an attempt was made to estimate the carbon sequestration potential of the forest estate in Ireland. Using 1999 inventory data, the Coillte forest estate was divided into the four main species groups for the purposes of calculating carbon sequestration potential (Table 6). Mean yield classes and rotation lengths were applied and the most appropriate carbon storage rates were taken from Dewar and Cannell (1992). Using this information carbon storage over the length of the rotation was calculated for each species group. The amount of carbon sequestered was calculated using the productive forest area (PFA) rather than the total forest area (TFA). The TFA under Sitka spruce for example, is 260,655 hectares. However only 221,557 hectares of this is productive (under trees). The additional 15% is made up of roads, rides and other unplanted areas. Although the vegetation found on this additional 15% of land may sequester carbon, it does not necessarily do so at the same rate as the forest crop and hence this area is excluded from these calculations. A more detailed breakdown of the area and carbon storage potential of each species group is outlined in Table 7. This shows that the forest area of 344,896 hectares stores 1.16 MtC/an. This converts to an average rate of 3.36 tC/ha/an. This is slightly higher than the figure of 2.97 tC/ha/an calculated using the method of Gallagher (1998). This higher carbon storage rate (3.36 tC/ha/an) is to be expected from the Dewar and Cannell (1992) model due to the fact that it considers the entire forest ecosystem, including soils, rather than forest biomass alone. In addition to the Coillte forest area there is a further ca. 160,000ha of private planting which, assuming the same average rate of carbon storage, stores approximately 0.54 MtC/an. This brings the national total to 1.7 MtC/an.

## 6.1 Kyoto Protocol and the Irish situation

With the signing of the Kyoto Protocol, the Irish nation is committed to limiting its greenhouse gas emissions to 13% above the 1990 level by the period 2008-2012. Total greenhouse gas emissions ($CO_2$ + $CH_4$ + $N_2O$) in Ireland in 1990 amounted to the equivalent of 56.9 Mt$CO_2$, (15.5 MtC) (Economic and Social Research Institute (ESRI), 1999). Thirteen percent of this is 7.4 Mt$CO_2$, (2 MtC). Thus the allowable annual limit, for the period 2008-2012, of greenhouse gas emissions (as $CO_2$ equivalent) will be 64.3 Mt$CO_2$, (17.5 MtC). In the absence of abatement measures it is clear that greenhouse gas emissions as predicted will exceed this limit shortly after the year 2000 (Table 8). In the case of $CO_2$ emissions, total Irish emissions in 1990 amounted to 30.7 Mt$CO_2$ (8.4 MtC). Thirteen percent of this is 3.99 Mt$CO_2$ (1.1 MtC). Thus the allowable annual limit for $CO_2$ emissions for the 2008-2012 period will be 34.7 Mt (9.5 MtC). Table 8 indicates that $CO_2$ emissions as predicted will exceed this level by the year 2000. With regard to $CH_4$ emissions, total Irish emissions in 1990 (as $CO_2$ equivalent) amounted to 17 Mt$CO_2$ (4.6 MtC). Thirteen percent of this is 2.21 Mt$CO_2$ (0.6 MtC). Thus the allowable annual limit for $CH_4$ emissions for the period 2008-2012 is the equivalent to 19.2 Mt$CO_2$ (5.2 MtC). Predicted $CH_4$ emissions by the year 2010 are actually below this level (Table 8). Finally, in the case of $N_2O$ emissions, total Irish emissions in 1990 (as $CO_2$ equivalent) amounted to 9.1 Mt$CO_2$ (2.5 MtC). Thirteen percent of this is 1.18 Mt$CO_2$ (0.3 MtC). Thus the allowable annual limit for $N_2O$ emissions for the period 2008-2012 is the equivalent to 10.3 Mt$CO_2$ (2.8 MtC). Predicted emissions of $N_2O$ by the year 2010 do not exceed this level.

Table 6. Carbon storage over the rotation length for the four main species groups in Irish forests.

| Species | TFA ha | PFA ha | Mean YC $m^3$/ha/yr | Rotation yr | Rate of C Storage tC/ha/yr[1] | C Mt |
|---|---|---|---|---|---|---|
| Sitka spruce | 260,655 | 221,557 | 16 | 45 | 3.6 | 35.89 |
| Other conifers | 130,626 | 111,032 | 12 | 45 | 3.0 | 14.99 |
| Oak/beech | 7,680 | 6,528 | 4 | 95 | 1.8 | 1.12 |
| Other broadleaves | 6,799 | 5,779 | 6 | 35 | 2.4 | 0.49 |

1 After: Dewar and Cannell (1992)

Table 7. Estimated carbon storage in Coillte forests using carbon storage rates from Dewar and Cannell (1992) and Coillte forest inventory data[1].

| Area (ha) & Carbon Storage (tC/an) for the four main species groups in Irish forests according to planting date. | | | | | | | | | | TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|
| Species | Pre 1920 | 1920-29 | 1930-39 | 1940-49 | 1950-59 | 1960-69 | 1970-79 | 1980-89 | 1990-99 | ha & MtC/an |
| Sitka spruce | 6<br>21.6 | 25<br>90.0 | 108<br>388.8 | 301<br>1,083.6 | 12,160<br>43,776.0 | 42,269<br>152,168.4 | 51,062<br>183,823.2 | 46,981<br>169,131.6 | 68,645<br>247,122.0 | 221,557<br>0.80 |
| Other conifers | 200<br>600.0 | 311<br>933.0 | 1,839<br>5,517.0 | 2,963<br>8,889.0 | 15,375<br>46,125.0 | 29,747<br>89,241.0 | 28,004<br>84,012.0 | 19,487<br>58,461.0 | 13,106<br>39,318.0 | 111,032<br>0.33 |
| Oak/beech | 1,683<br>3,029.4 | 125<br>225.0 | 753<br>1,355.4 | 950<br>1,710.0 | 1,046<br>1,882.8 | 617<br>1,110.6 | 277<br>498.6 | 343<br>617.4 | 734<br>1,321.2 | 6,528<br>0.01 |
| Other broadleaves | 220<br>528.0 | 63<br>151.2 | 273<br>655.2 | 485<br>1,164.0 | 536<br>1,286.4 | 589<br>1,413.6 | 644<br>1,545.6 | 1,094<br>2,625.6 | 1,875<br>4,500.0 | 5,779<br>0.02 |
| TOTAL | 2,109<br>4,179.0 | 524<br>1,399.2 | 2,973<br>7,916.4 | 4,699<br>12,846.6 | 29,117<br>93,070.2 | 73,222<br>243,933.6 | 79,987<br>269,879.4 | 67,905<br>230,835.6 | 84,360<br>292,261.2 | 344,896<br>1.16 |

Forecasts produced by the ESRI (1999) indicate that the energy consumption of the Irish economy is likely to increase rapidly over the next decade. The predicted growth in total fuel consumption is more than 55% between 1995 and 2010. The bulk of this increase will come from growth in oil (73% increase), electricity (82% increase) and gas (100% increase) consumption. Consumption of peat and coal is expected to decrease as people opt for cleaner and more efficient fuels. The predicted greenhouse gas emissions (represented as $CO_2$ & C equivalents) at different points in time to the year 2010 will increase accordingly (Table 8). According to ESRI (1999), if policies remain unchanged, Ireland may be releasing greenhouse gases equivalent to 75 $MtCO_2$ (20.5 MtC) into the atmosphere by 2010. This would amount to an increase of almost 32% on 1990 emissions.

From the figures produced by ESRI (1999) (Table 8) it appears that $CO_2$ emissions have been increasing since 1990. The predicted average increase for the period 2000-2010 is 1 Mt/yr. Although $CH_4$ emissions decrease from 1995-2000 they are predicted to increase again at a rate of 0.18 Mt/yr ($CO_2$ equivalent) for the period 2000-2010. Levels of $N_2O$ emissions are shown to have decreased since 1990 and are predicted to continue decreasing at an average rate of 0.01 Mt/yr ($CO_2$ equivalent) during the 2000-2010 period. Following these assumptions it is apparent that while emissions of $CO_2$ will be above that which is allowable, the surplus for all greenhouse gases will be lower because emissions of $CH_4$ and $N_2O$ will not reach 1990 +13% levels (Table 9).

The Kyoto agreement permits countries to offset surplus emission against carbon sequestered by forests over the period of the agreement (2008-2012). However, only plantations established post 1990 may be used in calculating the amount of carbon to be offset (Appendix 1). In addition, there is on-going debate as to the definition of reforestation within the Kyoto agreement. For the purposes of this report reforestation is not included in the calculations. However, should reforestation areas become eligible for inclusion in calculations, the amount of carbon which could be offset could be as much as 8.59 Mt over the period 2008-2012 (Appendix 2).

1 Data supplied by Coillte

Table 8. Forecast of Irish greenhouse gas emissions (Mt of $CO_2$ equivalent & Mt of C equivalent) 1990-2010. After: ESRI (1999).

| | 1990 | | 1995 | | 2000 | | 2010 | |
|---|---|---|---|---|---|---|---|---|
| | $CO_2$ | C | $CO_2$ | C | $CO_2$ | C | $CO_2$ | C |
| $CO_2$ | 30.7 | 8.4 | 34.1 | 9.3 | 39.7 | 10.7 | 49.8 | 13.6 |
| $CH_4$ | 17.0 | 4.6 | 17.1 | 4.7 | 15.8 | 4.3 | 17.6 | 4.8 |
| $N_2O$ | 9.1 | 2.5 | 8.1 | 2.2 | 7.7 | 2.1 | 7.6 | 2.1 |
| Total | 56.9 | 15.5 | 59.3 | 16.2 | 63.3 | 17.3 | 75.0 | 20.5 |
| Change on 1990 | - | | 4.3% | | 11.3% | | 31.9% | |

Table 9. Forecast of total and surplus greenhouse gas emissions[1] (Mt $CO_2$ and C equivalent) in Ireland for the Kyoto period 2008-2012.

| | | 2008 | 2009 | 2010 | 2011 | 2012 |
|---|---|---|---|---|---|---|
| $CO_2$ | $CO_2$ | 47.8 | 48.8 | 49.8 | 50.8 | 51.8 |
| | C | 13.0 | 13.3 | 13.6 | 13.9 | 14.1 |
| Surplus $CO_2$ | $CO_2$ | 13.1 | 14.1 | 15.1 | 16.1 | 17.1 |
| | C | 3.6 | 3.8 | 4.1 | 4.4 | 4.7 |
| $CH_4$ | $CO_2$ | 17.2 | 17.4 | 17.6 | 17.8 | 18.0 |
| | C | 4.7 | 4.7 | 4.8 | 4.9 | 4.9 |
| Surplus $CH_4$ | $CO_2$ | - | - | - | - | - |
| | C | - | - | - | - | - |
| $N_2O$ | $CO_2$ | 7.6 | 7.6 | 7.6 | 7.6 | 7.6 |
| | C | 2.1 | 2.1 | 2.1 | 2.1 | 2.1 |
| Surplus $N_2O$ | $CO_2$ | - | - | - | - | - |
| | C | - | - | - | - | - |
| Greenhouse gases ($CO_2$ + $CH_4$ + $N_2O$) | $CO_2$ | 72.6 | 73.8 | 75.0 | 76.2 | 77.4 |
| | C | 19.8 | 20.1 | 20.5 | 20.8 | 21.1 |
| Surplus greenhouse gases ($CO_2$ + $CH_4$ + $N_2O$) | $CO_2$ | 8.3 | 9.5 | 10.7 | 11.9 | 13.1 |
| | C | 2.3 | 2.6 | 2.9 | 3.2 | 3.6 |

1 Data for 2010 are from ESRI (1999). Data for 2008, 2009, 2011, 2012 assume constant increases of 1 Mt/yr ($CO_2$) ,-0.18 Mt/yr ($CH_4$) and -0.01 Mt/yr ($N_2O$).

## 6.2 Surplus $CO_2$ emissions

Thus, as matters currently stand, the carbon sequestered (1.14 Mt) by 353,569 ha of new forest (Appendix 1a) in 2008 may be offset against surplus emissions in that year. The corresponding figure for carbon sequestration in the year 2012 may be in the region of 1.40 Mt. Of course these figures assume that the planting targets as set out in the strategic plan for the development of the forestry sector in Ireland (Forest Service, 1996) are met. Assuming that these planting targets are achieved, then post 1990 Irish forests have the potential to sequester 6.34 MtC over the period 2008-2012. Over the same period surplus emissions will amount to 20.6 MtC. Thus carbon fixed by Kyoto forests would offset 31% of surplus $CO_2$ emissions. However, for a variety of reasons planting targets have not been reached in the forestry sector in recent years. This has a consequent effect upon the amount of carbon stored in forest ecosystems and the accumulated carbon surplus. Thus, for example, if 80% of the planting target is achieved, post 1990 forests could sequester a total of 5.54 MtC by the end of the 2008-2012 period. This would offset 27% of surplus $CO_2$ emissions. It is clear (Table 10) that failure to reach stated policy goals may have serious consequences in relation to offsetting accumulated $CO_2$ surpluses. As previously mentioned, should carbon sequestered on post 1990 reforestation sites be permitted for inclusion, then the total carbon sequestered during the Kyoto period could be almost 8.59 Mt and the proportion of surplus $CO_2$ offset could be as high as 42% (Table 11).

Table 10. Impact of forest planting programme (afforestation) upon carbon sequestration and $CO_2$ emissions surplus to year 2012.

| Planting target reached % | Accumulated surplus carbon emissions Mt | Total carbon sequestration in post 1990 forests Mt | Accumulated surplus offset % |
|---|---|---|---|
| 100 | 20.6 | 6.34 | 31 |
| 80 | 20.6 | 5.54 | 27 |
| 60 | 20.6 | 4.75 | 23 |
| 50 | 20.6 | 4.35 | 21 |

Table 11. Impact of forest planting programme (afforestation and reforestation) upon carbon sequestration and $CO_2$ emissions surplus to year 2012.

| Planting target reached % | Accumulated surplus carbon emissions Mt | Total carbon sequestration in post 1990 forests Mt | Accumulated surplus offset % |
|---|---|---|---|
| 100 | 20.6 | 8.59 | 42 |
| 80 | 20.6 | 7.48 | 36 |
| 60 | 20.6 | 6.38 | 31 |
| 50 | 20.6 | 5.84 | 28 |

## 6.3 Surplus greenhouse gas ($CO_2 + CH_4 + N_2O$) emissions

The Kyoto Protocol deals with the reduction of all greenhouse gases including $CO_2$. Although $CO_2$ emissions for the period 2008-2012 are predicted to exceed the allowable limit, $CH_4$ and $N_2O$ emissions are predicted to be below the allowable limits for the same period. For this reason surplus emissions to be offset will in fact be less than those when dealing with $CO_2$ alone. Assuming that planting targets are achieved and post 1990 Irish forests reach their potential to sequester 6.34 MtC over the period 2008-2012, then 43% of surplus greenhouse gases accumulated during the same period would be offset. If 80% of the planting target is achieved, post 1990 forests could sequester a total of 5.54 MtC by the end of the 2008-2012 period. This would offset 38% of surplus greenhouse gas emissions (Table 12). Should carbon sequestered in post 1990 forests established on reforestation sites be permitted, then the total carbon sequestered during the Kyoto period could be almost 8.59 Mt and surplus greenhouse gas offset could be as high as 59% (Table 13).

Table 12. Impact of forest planting programme (afforestation) upon carbon sequestration and greenhouse gas emissions surplus to year 2012.

| Planting target reached % | Accumulated surplus greenhouse gas emissions MtC equivalent | Total carbon sequestration in post 1990 forests Mt | Accumulated surplus offset % |
|---|---|---|---|
| 100 | 14.6 | 6.34 | 43 |
| 80 | 14.6 | 5.54 | 38 |
| 60 | 14.6 | 4.75 | 33 |
| 50 | 14.6 | 4.35 | 30 |

Table 13. Impact of forest planting programme (afforestation and reforestation) upon carbon sequestration and greenhouse gas emissions surplus to year 2012.

| Planting target reached % | Accumulated surplus greenhouse gas emissions MtC equivalent | Total carbon sequestration in post 1990 forests Mt | Accumulated surplus offset % |
|---|---|---|---|
| 100 | 14.6 | 8.59 | 59 |
| 80 | 14.6 | 7.48 | 51 |
| 60 | 14.6 | 6.38 | 44 |
| 50 | 14.6 | 5.82 | 40 |

# 7. Valuing carbon sequestration and storage in Irish forests

There are three approaches to valuing carbon sequestration and storage benefits of afforestation (Clinch, 1999):

- The Damage Avoided Approach: values a tonne of carbon sequestered by the cost of the damage that would have been done by global warming had that tonne of carbon not been sequestered.
- The Offset Approach: values a tonne of carbon sequestered by the cost of substituting a non-carbon fuel for a fossil fuel at the margin (i.e. the next cheapest alternative method of carbon sequestration, as $CO_2$ reduction technology does not exist).
- The Avoided Cost of Compliance Approach: values a tonne of carbon sequestered by the avoided cost of compliance with a global policy for $CO_2$ emissions reduction. (In the case of a fixed emission quota, the value is identical to the Offset Approach value).

Although the Damage Avoided Approach is the most appropriate measure of global carbon sequestration benefits, it is not the most suitable method for measuring the value of carbon sequestration in the relatively small Irish afforestation area (economy). Following the Avoided Cost of Compliance Approach, Clinch (1999) calculated the net sequestration benefits of 1ha of afforestation for three species at several discount rates and assuming the cost of a tradeable emission permit to be £15 per tonne of carbon (Table 14). This latter figure assumes that a global emissions trading scheme will exist. In the absence of such a scheme the actual figure may be considerably greater than £15 per tonne.

At the 5% discount rate, the present value of the sequestration benefits for 1ha of YC18 Sitka spruce is £155. Similarly, 1ha of YC6 oak would also have a present carbon sequestration value of £155. Using this figure of £155/ha as the present 'carbon sequestration' value of forest crops and assuming that planting targets are fully achieved, then the present carbon sequestration value of new forests established in the period 1990-2012 (433,569 ha) would be approximately £67 million. However, if actual planting falls progressively behind targets, the financial penalty will increase proportionately (Table 15). Should carbon sequestered in post 1990 forests established on reforestation sites be permitted, then the present carbon sequestration value of all afforestation and reforestation forests could be as much as £91 million (Table 16).

Table 14. Net present sequestration benefits (£) of 1ha of afforestation assuming a perpetual sequence of rotations, with the estimated cost of a tradeable emission permit at £15/tC. After: Clinch (1999).

| Species | YC | Rotation | Discount Rate | | | |
|---|---|---|---|---|---|---|
| | $m^3$/ha/yr | yr | 2% | 5% | 8% | 11% |
| Sitka spruce | 18 | 40 | 325 | 155 | 80 | 50 |
| Norway spruce | 14 | 50 | 255 | 110 | 55 | 30 |
| Oak | 6 | 80 | 420 | 155 | 75 | 40 |

Table 15. The present value of carbon sequestration by new forests established in the period 1990-2012 assuming various planting rates.

| Planting target reached<br>% | Area planted in period 1990-2012<br>ha | Present carbon sequestration value[1]<br>£ 000,000 |
|---|---|---|
| 100 | 433,569 | 61 |
| 80 | 375,569 | 58 |
| 60 | 317,569 | 49 |
| 50 | 288,569 | 44 |

Table 16. The present value of carbon sequestration by all forests established in the period 1990-2012 assuming various planting rates.

| Planting target reached<br>% | Area planted in period 1990-2012<br>ha | Present carbon sequestration value<br>£ 000,000 |
|---|---|---|
| 100 | 587,097 | 91 |
| 80 | 506,584 | 78 |
| 60 | 425,898 | 66 |
| 50 | 385,600 | 59 |

1 At 5% discount rate

# 8. The current situation and future policy implications

The strategic plan for the Irish forestry sector (Forest Service, 1996) provides a great opportunity for carbon sequestration in Irish forests. With current annual afforestation targets of 25,000ha until the year 2000 and 20,000ha per annum thereafter, (20% of which is with broadleaved species), Irish forest crops can contribute significantly to the mitigation of climate change through their ability to store carbon. The species profile in the Irish forest sector allows for carbon sequestration in both the long and short terms. Relatively fast growing coniferous species store carbon rapidly over the short term while slower growing broadleaf species, although they sequester carbon at a lower rate, act as long term carbon stores.

The estimate of carbon storage in Irish forest plantations (average: 3.36 t/ha/an) given in this report, is as accurate as the current available information allows. However, there is considerable potential for an improvement in this estimated figure. Although the model (Dewar and Cannell, 1992) used is the best currently available for estimating carbon storage rates in Irish forests, as with all mathematical models and equations, several assumptions are made. These include, assumed rates of carbon transfer between pools, assumed rates of soil, biomass and product decay and the assumption that all crops follow the growth patterns of the British Forestry Commission yield models (Edwards and Christie, 1981).

When using the Dewar and Cannell (1992) model to estimate carbon storage in Irish forests there are three main factors which appear to be critical to the accuracy of the estimate. These are the yield models, the BEF and soil carbon dynamics.

The most important of these factors is the suitability of the British Forestry Commission yield models to predict forest crop production in Ireland. This is of primary importance as yield models are the foundation of this carbon storage model. Although there are few published data, there is evidence (Gallagher, 1972) that Irish forest crops may have a greater cumulative volume production for any given top height than is shown in the British Forestry Commission yield models. As a result, rotation lengths may be considerably shorter. In addition, due to financial considerations, rotations for Irish forest crops are frequently shorter than the rotation of MMAI. These differences would result in significantly higher carbon storage rates in forest crops in Ireland. Thus, the Dewar and Cannell model may significantly underestimate the carbon storage rates of Irish forest plantations.

Other factors, directly linked with this model, also appear to be both critical and poorly documented. Although the data available are sparse, particularly in the Irish context, it appears that the BEF may be considerably higher in Irish forests than the figure (1.4) used by Dewar and Cannell (1992). If this is so, it is possible that the rate of carbon storage in Irish forest crops is much higher than the rate estimated in this report. At this point it is worthy of note that using a BEF of 2.8 would result in a 73% increase in carbon storage (Dewar and Cannell, 1992).

Irish forest plantations have a very young age profile. Almost 25% of the forest area has been established since 1990 (Farrington, pers. comm.). Despite the fact that younger crops have a higher BEF than mature crops of similar species, they do not have a higher rate of carbon storage than that estimated in Section 6 of this report. This is due to the fact that the model (Dewar and Cannell, 1992) used is based on mean annual increment (MAI) rather than current annual increment (CAI). So in fact, the rate of carbon storage estimated for any particular species is an average rate over the crop rotation. While this model uses the same average rate of carbon storage over the entire crop rotation, a model based on CAI would use a different rate of carbon storage depending on the age of the crop at a particular time. Both methods should, however, produce the same figure for total carbon storage of any crop at the end of the rotation. This model based on MAI overestimates the rate of storage in both very young crops and those which have passed the age of MMAI (i.e. when CAI<MMAI). It also underestimates the rate of storage in rapidly growing crops (i.e. when CAI>MMAI). Therefore over the entire rotation of the crop these over- and under- estimates balance out and hence one average rate of carbon storage can be applied. This is clearly evident from Figure 5. A model baesd on MAI in this situation actually overestimates the carbon storage in the forest plantation until the crop is approximately 20 years of age. Therefore, using a model based on MAI to calculate the carbon being sequestered by a forest during the first Kyoto period (2008-2012) will in fact overestimate the amount of carbon being sequestered during that time span.

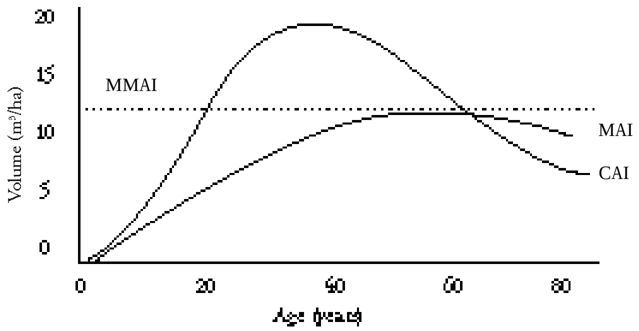


Figure 5. Patterns of volume increment in an even aged stand.
After: Edwards and Christie (1981)

It is also clear from this report that the soil carbon pool is the largest and most important carbon storage pool in the forest ecosystem. This is a poorly understood area with little information available on the carbon dynamics in soil and in particular in forest soils. The effects of different management practices on soil carbon storage have been documented but not specifically for the Irish situation. Therefore, in order to estimate the storage capacity of the soil carbon pool accurately, an in-depth understanding of soil carbon dynamics is necessary.

Forest plantations have the potential to abstract large quantities of $CO_2$ from the atmosphere and to store large quantities of carbon in wood. Calculations outlined in this report indicate that Irish forests fix in excess of 3.36 tC/ha/an. The actual figure may be significantly greater than this but research data relating to the rate of growth and volume production pattern of trees in Ireland which would permit the calculation of a more accurate estimate are not available.

However, after some time all forests reach a state of $CO_2$ equilibrium. Thus new land must be continually planted with trees in order to achieve continual net carbon sequestration. The number of years before a forest reaches $CO_2$ equilibrium depends very largely upon species selection and forest management. Short term carbon storage can be maximised by planting fast growing species such as Sitka spruce and poplar on unplanted sites and managing them using advanced silvicultural techniques. Long term carbon storage on the other hand is optimised by planting slower growing species such as oak and beech on long rotations and by setting aside large areas of land where trees would be allowed to grow to maximum size and thereafter remain in place. Because the current Irish forest estate is young it will continue to be a net carbon sink for the next two to three decades at least. In addition the expansion of the national forest by 25,000 ha/an to the year 2000 and by 20,000 ha/an thereafter will ensure that Irish forests continue to accumulate carbon when established forests reach equilibrium.

Although this report provides a preliminary estimate of the carbon storage potential of Irish forest ecosystems, much research will be necessary to refine this estimate and to produce a more accurate Irish carbon storage figure. Additional research is necessary to examine the three most critical areas (the yield models, the BEF and soil carbon dynamics) in order to adapt the model and produce results appropriate to Ireland. Until this basic information is gathered it is only possible to make assumptions on the present situation and the future potential for carbon storage in Irish forest ecosystems.

# APPENDICES